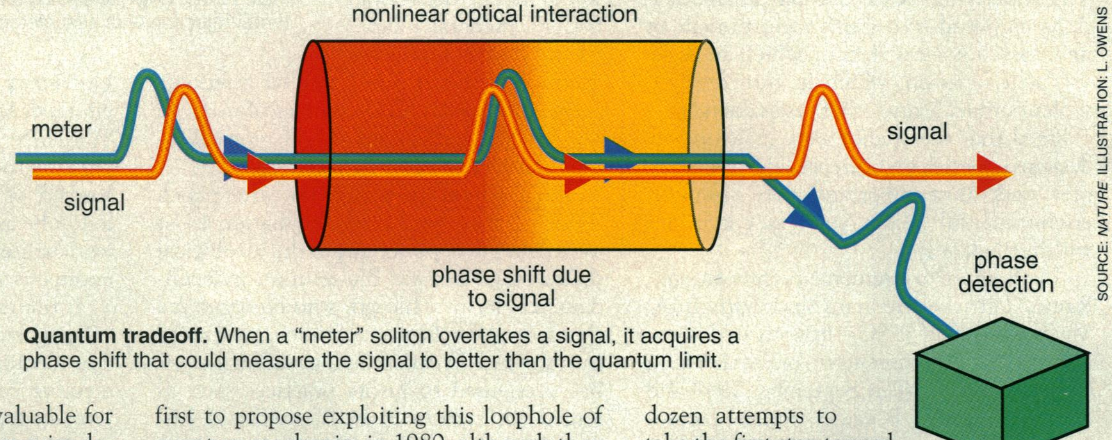
QUANTUM PHYSICS

Heisenberg's Heirs Exploit Loopholes in His Law

"Quantum mechanics," so the saying goes, "is not just a good idea; it's the law!" And among the most famous items in that scientific code is the Heisenberg uncertainty principle, which holds that any measurement of a quantum mechanical system, such as a light wave or an atom, will disturb the system in an unpredictable manner. The more precise the measurement, the greater the disturbance. In other words, says Jeff Kimble, a physicist at the California Institute of Technology, "if you open up a hole to look at the state of a quantum system, the same hole that lets information out, lets fluctuations in."

The result is an intrinsic barrier of fuzziness to our knowledge of, say, the amplitude or phase of a light wave. In the past few years, however, Kimble and other researchers in a quartet of collaborations have managed to show that the Heisenberg uncertainty principle is a little like the tax code: It cannot be broken with impunity, but it has loopholes that—with sufficient ingenuity—can be profitably exploited. The result is a series of experiments that use sophisticated optical techniques to extract information from a quantum mechanical system without disturbing the variable being measured. This quantum sleight of hand opens the way to measurements so precise, says Philippe Grangier of the French Institut d'Optique Théorique et Appliquée, that they can reveal the fundamental "graininess" of light: "the fluctuations in intensity caused by its photon nature."



Quantum tradeoff. When a "meter" soliton overtakes a signal, it acquires a phase shift that could measure the signal to better than the quantum limit.

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That ability to sneak around the limit of accuracy set by the uncertainty principle might be valuable for fundamental measurements that require detecting signals so weak and transitory that they push the limits of quantum mechanical precision. And it's the first step toward a more distant goal in fundamental physics: demonstrating the concept of quantum nondemolition, or QND, a term coined by Moscow State University physicist Vladimir Braginsky. In theory, a measurement that exceeds the quantum limit and does so without introducing noise into the signal—leaving it "undemolished"—qualifies as QND.

To prove the concept, however, physicists will have to make a pair of measurements of the same system. The first measures the variable of interest, and the second remeasures it, showing that the variable hasn't been disturbed by the initial measurement. Making these measurements once has proven over the years to be hard enough. But if physicists could repeat the trick, it might have applications of its own—for example, in telecommunications, where QND could lead to an "optical tap" that would enable multiple users on a communications network to read out the same information from a single laser beam, leaving the information undisturbed for other users.

Evasive measures. The loophole these physicists are exploiting is the possibility of channeling all the uncertainty generated by measuring one quantum variable (a laser beam's intensity, for example) onto a related variable, known as the conjugate observable (the beam's phase). The strategy is called back-action evasion, says Edgard Goobar, a visiting scientist at the University of California, Santa Barbara. "We put the back action of the measurement on the observable that we're not interested in measuring."

Braginsky, Kip Thorne of Caltech, and Yuri Vorontzov of Moscow State were the first to propose exploiting this loophole of quantum mechanics in 1980, although they were striving for a workable gravity wave detector, not quantum optics or telecommunications. Braginsky explains that he and his colleagues envisioned a detector consisting of a huge bar, weighing perhaps 10 tons, with subtle measuring devices monitoring its behavior. They imagined that a passing gravity wave—a ripple in spacetime generated by some cataclysmic process far off in the universe—would nudge the bar into oscillating back and forth.

The catch was that the oscillations would likely be as small as 10^{-19} centimeters, lasting no more than 10^{-3} seconds. Those oscillations lie below the quantum limit of any conceivable optical or electromagnetic measurement system, and therefore any measurement would introduce so much uncertainty that physicists would have no idea if they were picking up the effect of a gravity wave—or just "noise" leaking into their quantum system from the effort to measure it.

The solution Braginsky and his colleagues proposed was to use two perpendicular bars to detect the oscillations; on one they could accurately measure the sine of the amplitude while imparting complete uncertainty to the cosine; on the other they could measure the cosine of the amplitude, sacrificing information about the sine. "By combining the results of the two measurements on the two bars," says Thorne, "you can get as good an accuracy as you wish, [since] both bars are being driven by the same gravity wave." Because this QND strategy would leave the measured variables unscathed by the act of measurement, it would allow repeated measurements of the bars to confirm the reality of the passing wave.

The scheme was never tested, because in the mid-1980s, researchers at Caltech and MIT proposed an alternative scheme for capturing gravity waves—now known as LIGO—that didn't require QND. The pursuit of QND moved into quantum optics, which is a standard testing ground for tenets of quantum mechanics because it offers many sophisticated schemes for detecting quantum states of light. The result has been a half-dozen attempts to take the first step toward QND—a back-action-evading measurement—relying on almost as many different technological strategies.

The only common standard in this race has been the requirement that the accuracy of the measurement exceed the so-called standard quantum limit. For light that limit is set by the vacuum fluctuations: random fluctuations in the intensity and phase of photons that make up the light. To see how their results measure up, says Grangier, physicists compare the first, back-action-evading measurement with the electric current generated by shining the beam of light on a photodiode. The current will register all the variations in the beam, including the vacuum fluctuations. If the difference between the two measurements is less than the vacuum fluctuations, the first measurement has exceeded the standard quantum limit.

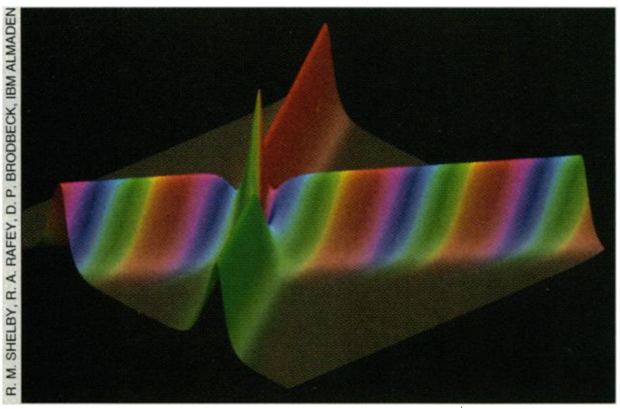
In one set of efforts to beat this standard, experimenters have tried to extract information about a light pulse (the signal) by playing another pulse (the meter) off it. The rationale for this strategy is that when the two light pulses interact in a so-called nonlinear medium, the meter beam can pick up information about the intensity of the signal, apparently without affecting it. The interaction leaves its mark on the signal only by altering its phase. That tradeoff seemed to open the way to a measurement that would exceed the quantum limit, because all of the back action would be funneled into the signal's phase.

The first demonstration of this measurement principle came in 1986, when Mark Levenson and his colleagues at IBM passed two laser beams of different wavelengths through an optical fiber that had an appropriate nonlinear property: A signal propagating down the fiber would alter its index of refraction by an amount that depended on the signal's intensity. That change in refractive index alters the speed of light in the medium, which in turn shifts the phase, or timing, of a meter beam passing through the fiber at the same time. By separating and analyzing the two beams after they emerged from the fiber, Levenson and his colleagues were able to show that variations in the amplitude of the signal showed up faithfully as variations in the phase of the meter.

Not faithfully enough, however: Levenson's experiment proved that such a measurement of signal beam by a meter beam was possible, but the correlation between signal and meter failed to transcend the standard quantum limit. It did, however, inspire Grangier and his colleagues to make their own bid for a back-action-evading measurement. "My idea," he says, "was to use something much more nonlinear than Levenson's fiber, so instead I used atomic vapor—sodium atoms—in a vacuum chamber." When Grangier and his colleagues fired a signal and a meter beam into this livelier medium, as they reported last year in *Physical Review Letters*, the measurement of signal amplitude matched the signal itself with a precision greater than the quantum limit.

But out there at the quantum limit Grangier isn't alone. Two other groups have pursued related strategies to exploit the loopholes in Heisenberg's legalese. One set of experiments, reported by Kimble and his colleagues Silvania Pereira and Z.Y. Ou this past January in *Physical Review Letters*, achieved an even closer match between meter and signal by using a scheme in which signal and meter are two different components of the same beam. Meanwhile, Yoshihisa Yamamoto of Stanford and Stephen Friberg of the NTT Basic Research Laboratories in Japan have been developing a technique for exceeding the quantum limit that, while less successful so far than Grangier's or Kimble's setup, could be more versatile.

Shifty solitons. Yamamoto and Friberg showed that the exotic nonlinear materials and laser pulses Grangier and Kimble used can be replaced by a single optical fiber carrying a kind of signal called a soliton, which is widely used for communications. Solitons, solitary waves that will not disperse because of the properties of the medium, interact in the same way as do laser pulses in a strongly nonlinear medium: When they collide, the intensity of one—the number of photons in it—alters the phase of the other.



R. M. SHELBY, R. A. RAFEY, D. P. BRODBECK, IBM ALMADEN

When solitons collide. A computer simulation shows the phase shift *(red to green)* in the meter soliton.

As a result, Yamamoto and Friberg conceived the strategy of sending a signal soliton down the fiber, followed by a meter soliton at a different wavelength that would propagate faster in the fiber, overtake the original signal, and "measure" it. The phase shift of the meter soliton should reveal the intensity of the signal soliton, while the signal should come out of the interaction with nothing altered except its phase. The strategy proved to have technical problems that kept it from exceeding the standard quantum limit. But because of its simplicity, it did manage to excite the quantum optics community, says Kimble. "If it had worked to [the quantum] level," he says, "everyone would be doing it now. It is clearly a technique with an exciting future."

In particular, says Gunnar Björk of Stanford, one could imagine harnessing solitons to make multiple back-action evading measurements of a single signal. "You could launch several probe solitons [down the same fiber]. They would all travel at the same speed, but faster than the signal. They would, one by one, overtake the signal and measure the photon number of the same pulse." Providing all of the meter solitons came up with the same value for photon number, that experiment would provide a formal demonstration of QND. And because the setup would use the same basic elements as standard fiber-optics communications, it might be readily turned to technological purposes.

But even before that vision of colliding solitons is realized, its technological appeal could be stolen by a scheme that achieves the same end—repeated measurements of the same signal—by taking precisely the opposite approach. Instead of striving to measure a signal without disturbing it, this scheme—described last September in *Physical Review Letters* by Grangier's group and, independently, by a collaboration from the Royal Institute of Technology in Sweden—destroys the signal completely in the process of measurement, then recreates a relatively faithful replica of the measured signal and sends it on its way.

Instead of probing the signal with another light wave, experiments based on this philosophy rely on high-efficiency detectors. By converting the amplitude of an optical beam into an electrical current, these detectors destroy the beam and all information about its phase. That's exactly what opens the way to an intensity measurement surpassing the quantum limit, says Björk, a member of the Swedish collaboration. "You gain all the information there is in the photon number," says Björk, "and what you have to trade off is to have total back action on the phase."

The current can then be fed into efficient light-emitting diodes. The result is a resurrected beam that, at least in principle, says Goobar, another member of the Swedish team, "is an exact copy of the incoming beam," except for a difference in phase. The main barrier to developing this scheme into a workable "quantum repeater" technology is inefficiency in the light-emitting diodes, says Björk. Even so, Grangier thinks that if the goal is to get information out of a beam repeatedly without degrading the signal to the point of losing it, this total demolition method may be the best bet yet (also see Yamamoto's Perspective on p. 1394).

To researchers intent on a more fundamental goal—proving the principle of QND—a good imitation is not enough, however. The signal beam has to remain sacrosanct no matter how many times it is probed. Kimble likes to quote a 1980 *Reviews of Modern Physics* article written by Braginsky, Thorne, and Carleton Caves of the University of New Mexico: "The key feature of such a nondemolition measurement is repeatability—once is not enough!" Agrees Grangier, "It would certainly be better to do it twice." But so far, he adds, "it was not so easy to do it once."

–Gary Taubes